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VARIABILITY OF SALTWATER FLOW IN THE HOBURG CHANNEL, BALTIC SEA: IN SITU MEASUREMENTS VS NEMO MODELLING

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Abstract

A half-year long time series of the bottom layer velocity measured in situ in the Hoburg Channel displayed seven-day oscillations of the saltwater flow. The flow was characterized by alterations of surges with the increase of northward velocity to approximately 0.2–0.3 m/s and blockages when the northward velocity vanishes or becomes small negative. The measured time series of the northward velocity component was surprisingly highly correlated with the simulation by NEMO reanalysis at the correlation coefficient of 0.82 and the 95 % confidence limits of 0.76–0.86. The seven-day oscillations were accompanied by almost synchronous oscillations of the southeast component of the wind vector. It can be considered convincing evidence that the seven-day oscillations in the saltwater flow were caused by wind forcing.

Keywords: Tilt current meter, bottom layer, Baltic Sea, saltwater flow, NEMO, wind forcing, near bottom currents, correlation

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ИЗМЕНЧИВОСТЬ ПОТОКА СОЛЕНОЙ ВОДЫ В КАНАЛЕ ХОБУРГ, БАЛТИЙСКОЕ МОРЕ: ИЗМЕРЕНИЯ И МОДЕЛИРОВАНИЕ NEMO

Статья поступила в редакцию 28.12.2023, после доработки 13.05.2024, принята в печать 14.05.2024

Аннотация

Полугодовой временной ряд скорости течения в придонном слое, измеренный в проливе Хобург, показал семидневные колебания потока соленой воды. Течение характеризовалось сменой нагонов с увеличением скорости, направленной на север, примерно до 0,2–0,3 м/с и блокировок, когда скорость в северном направлении исчезала или принимала малые отрицательные значения. Измеренные временные ряды северной компоненты скорости на удивление хорошо коррелировали с модельной скоростью течения, полученной с помощью реанализа NEMO. Коэффициент корреляции составлял 0,82 при 95 % доверительном интервале [0,76, 0,86]. Семидневные колебания сопровождались практически синхронными колебаниями юго-восточной составляющей вектора ветра. Это можно считать убедительным доказательством того, что семидневные колебания потока соленой воды были вызваны ветровым воздействием.

Ключевые слова: Инклинометрический измеритель скорости течения, придонный слой, Балтийское море, поток соленой воды, модель NEMO, ветровое воздействие, придонные течения, корреляция

1. Introduction

Saltwater inflows from the North Sea are known as the only process ventilating the Baltic Sea deep waters [1, 2]. For this reason, saltwater dynamics and deep water currents remain a challenge for the Baltic Sea oceanographers involved in the in situ measurements and modeling [3–16]. The comparison of in situ measurements

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of deep water currents versus modelling results is therefore an important test of the adequacy of the Baltic Sea circulation models. Zhurbas et al. [12] reported on a reasonable agreement of the mean currents and standard deviations modelled by GETM and the in situ velocity measurements in the bottom layer of the Bornholm and Gotland deeps [17, 18].

The Hoburg Channel (HC), a sloping-down underwater trough which connects the Słupsk Furrow on the southwest and the Gotland Deep on the northeast (Fig. 1), is the only pathway for the saltwater flow to enter the deep basins of the northern Baltic Proper. Since 2016, the Shirshov Institute of Oceanology has been conducting monitoring measurements of bottom currents on the eastern slope of the HC at a point with coordinates (19.13°E, 55.88°N). There were several causes to choose this location for the monitoring measurements. Firstly, it is located directly on the pathway of saltwater flow. Secondly, due to a topography constriction created by the Klaipeda Bank (see Fig. 1), this point is located in a "bottle neck" for the northeast saltwater flow which therefore can be considered as a hotspot for bottom friction, mixing and dissipation [12, 14]. And third, but not least important, this point is located in the economic zone of Russia and is therefore always available for deployment of moored instruments without permission from other countries.

Acoustic velocity profilers, which have been widely using in oceanography last decades, are of little use in a thin bottom layer due to the reflection of the acoustic signal. This niche can be occupied by the tilt current meter (TCM), a relatively cheap and easy-to-manufacture device suspended at a minimum distance above the bottom [14]. The objective of this work is providing the comparison of the in situ measurements of saltwater flow velocity in a thin bottom layer of HC by TCM and the results of NEMO marine reanalysis.

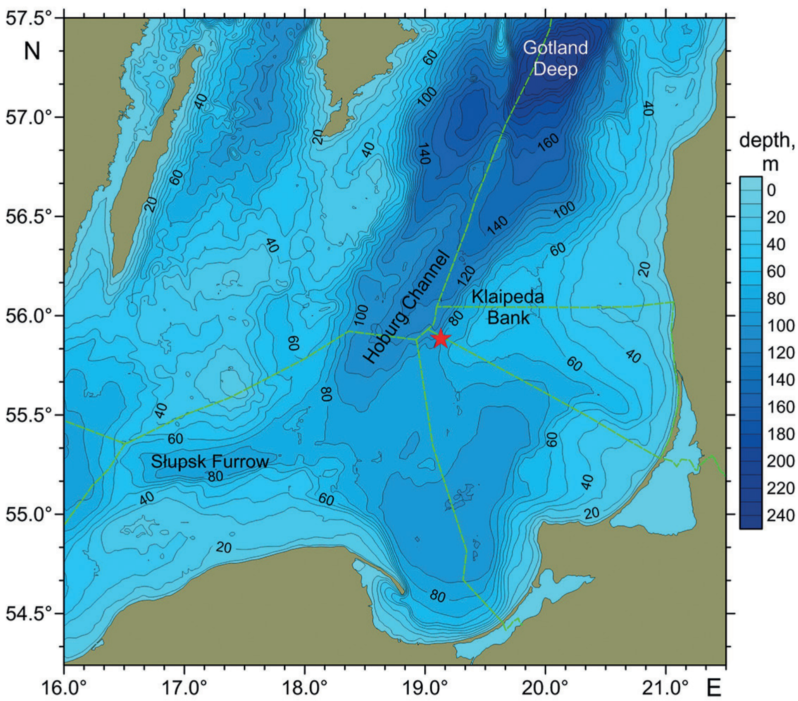

Fig. 1. Bathymetric map of the southeastern Baltic Sea. The TCM deployment location is marked with a red asterisk. The boundaries of economic zones are shown with a green dashed line

2. Materials and Methods

Measurements of current velocity in a thin bottom layer were performed with TCM, an autonomous device of own design [14]. The TCM was anchored at 1 m height above the bottom at a point with coordinates (19.13°E, 55.88°N) where the sea depth is 85 m and which is located on the eastern slope of HC directly on the pathway of saltwater flow. The time series of the velocity components with 10 min time step measured by TCM during the period of 163 days from November 6, 2022 to April 18, 2023 was low-pass filtered with 1 day window to remove inertial oscillations and higher frequency fluctuations. As a result, time series of velocity components u and v of $163 \times 4 = 652$ items long with the time step of 6 h were compiled for further processing and comparison with results of modelling.

The release of the latest version of the Baltic Sea reanalysis, NEMO-Nordic 2.0 [19], was used to compile the modelled time series u, v, temperature T, and salinity S with 6 h time step for the same period at the same location. The only difference between the measured and modelled velocity time series was the height above the bottom which was $h = 1$ m for the TCM measurements and $h = 5.5$ m for the NEMO simulation where the thickness of the closest-to-bottom model layer was $2h = 11$ m. The hourly time series of u, v, T, and S on the model grid of 1 nautical mile spacing in the Baltic Sea for the period 06.11.2022–18.04.2023 were downloaded from https://data.marine.copernicus.eu/product/BALTICSEA_ANALYSISFORECAST_PHY_003_006/download?dataset=cmems_mod_bal_phy_anfc_PT1H-i_202311 (last access on Dec 23, 2023).

In this study we also used the hourly time series of the 10 m level wind velocity from the ERA5 reanalysis downloaded through https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5 (last access on Dec 23, 2023).

3. Results

Even a prompt look at a plot of the v component velocity time series indicates an extremely high correspondence between the measured and simulated saltwater flow variability in the bottom layer of HC (Fig. 2). This visual perception is confirmed by calculations: correlation coefficient between the measured and simulated time series of v was found to be 0.82 at the 95 % confidence interval of [0.76, 0.86]. The v time series are characterized by undulations of the northward velocity component mainly between –0.05 m/s and 0.25 m/s with the period of approximately 7 days and the mean value of 0.106 m/s and 0.094 m/s for the TCM and NEMO, respectively.

The seven-day period of velocity fluctuation is clearly identified at velocity spectra (Fig. 3). The velocity spectra also display a peak related to inertial oscillations with the period of 14.4 hours. At frequencies lower than the inertial frequency, the velocity spectra obtained from field measurements and simulations are almost identical — the difference is within the 95 % confidence limits. At frequencies above the inertial frequency, the simulated velocity spectrum falls off faster than the measured velocity spectrum, since the hydrostatic model is unable to reproduce short-period internal waves.

The velocity hodograph (Fig. 4) calculated by integrating the measured and simulated time series displays almost straight-line displacements at the angle $\varphi = 96°$ and 74°, respectively, where φ is counted counterclockwise from the east (or from the x axis).

The spatial structure of the seven-day undulations of saltwater flow in HC is illustrated in Figs. 5 and 6, where vertical profiles of velocity components and maps of the bottom layer velocity simulated by NEMO are presented for two moments marked by black triangles on the time axis of Fig. 2. The two moments, November 12 and 16, 2022, correspond to local maximum and minimum of the northward velocity of saltwater flow, respectively (see Fig. 2). In the first moment, the v component is maximum in the bottom layer reaching 0.2 m/s, decreases to 0.05 m/s at the top of the permanent halocline (18 m depth), and is vanishingly small in the upper mixed layer (less than 0.01 m/s). In the second moment, the v component varies from –0.09 m/s to –0.06 m/s in the saltwater layer and from –0.03 m/s to –0.02 m/s in the upper mixed layer. Therefore, the northward saltwater flow being maximum in the first moment is entirely blocked in the second moment.

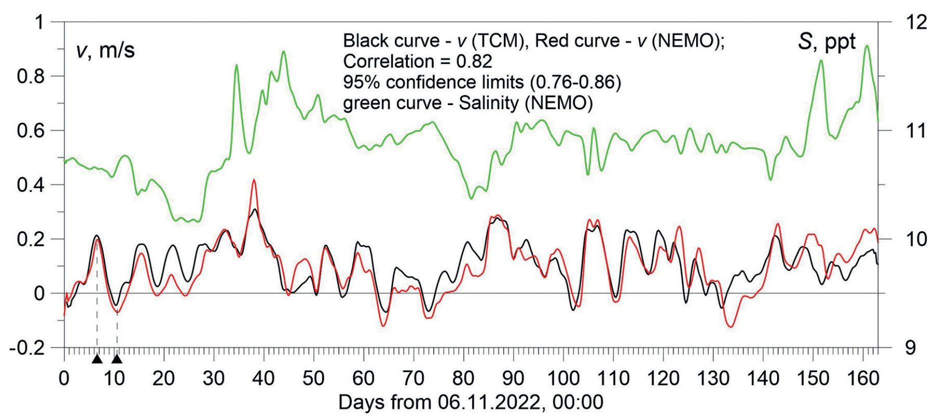

Fig. 2. Low-pass filtered time series (periods ≥ 1 day) of the v-component of velocity measured by TCM and simulated by NEMO (black and red curves, respectively), and salinity simulated by NEMO (green curve) in the bottom layer of HC for a 163 day period from November 6, 2022 to April 18, 2023

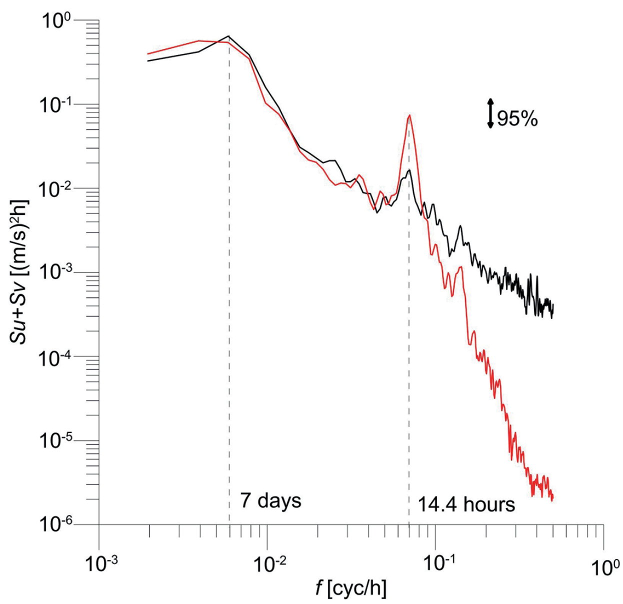

Fig. 3. Spectral density of velocity fluctuations in the bottom layer measured by TCM (black curve) and simulated by NEMO (red curve). Both the measured and modeled spectra have maxima at periods of 7 days and 14.4 hours, the former is probably related to the synoptic wind stress variability and the latter is obviously caused by inertial oscillations. Note that the inertial oscillation maximum from the model is more energetic than that from the *in situ* measurements. A suppression of the measured inertial oscillations is probably caused by the closeness of the measurement point to the steep bottom (approx. 1 m height above the seabed)

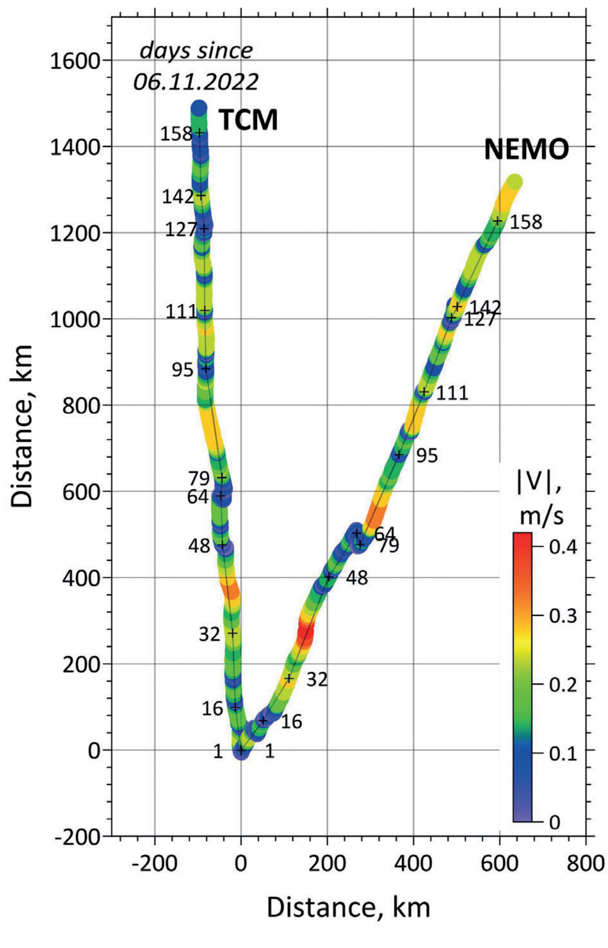

Fig. 4. Hodograph calculated from the 163 day velocity time series in the bottom layer of HC measured by TCM and simulated by NEMO

To determine the cause of blocking the northward flow of saltwater in HC, let's turn to the maps of the bottom layer current superimposed by wind velocity maps for the same two moments (Fig. 6). It is clearly seen that the enhanced saltwater flow to the north in HC on November 12, 2022 was accompanied by a westerly wind, while the blockage of saltwater flow the north on November 16, 2022 was accompanied by an easterly wind. Therefore, we can assume that the seven-day fluctuations of saltwater flow through HC are controlled by wind forcing.

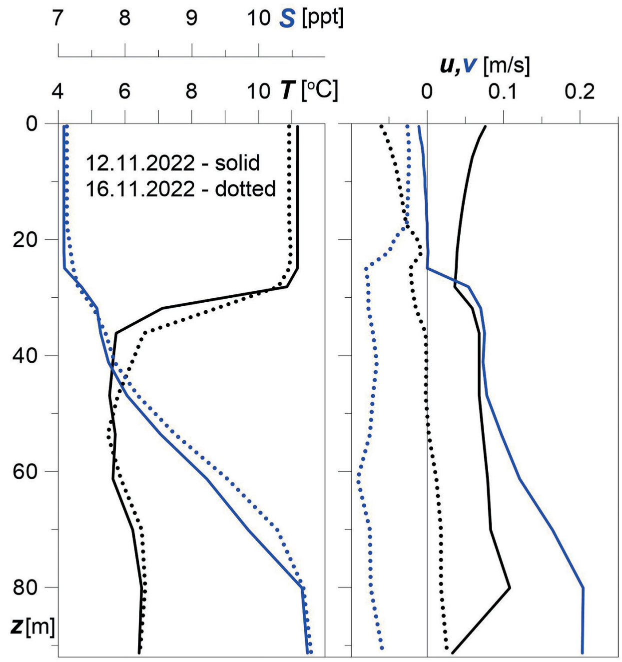

Fig. 5. Vertical profiles of temperature *T*, salinity *S*, and velocity components, *u* and *v*, for November 12 and 16, 2022

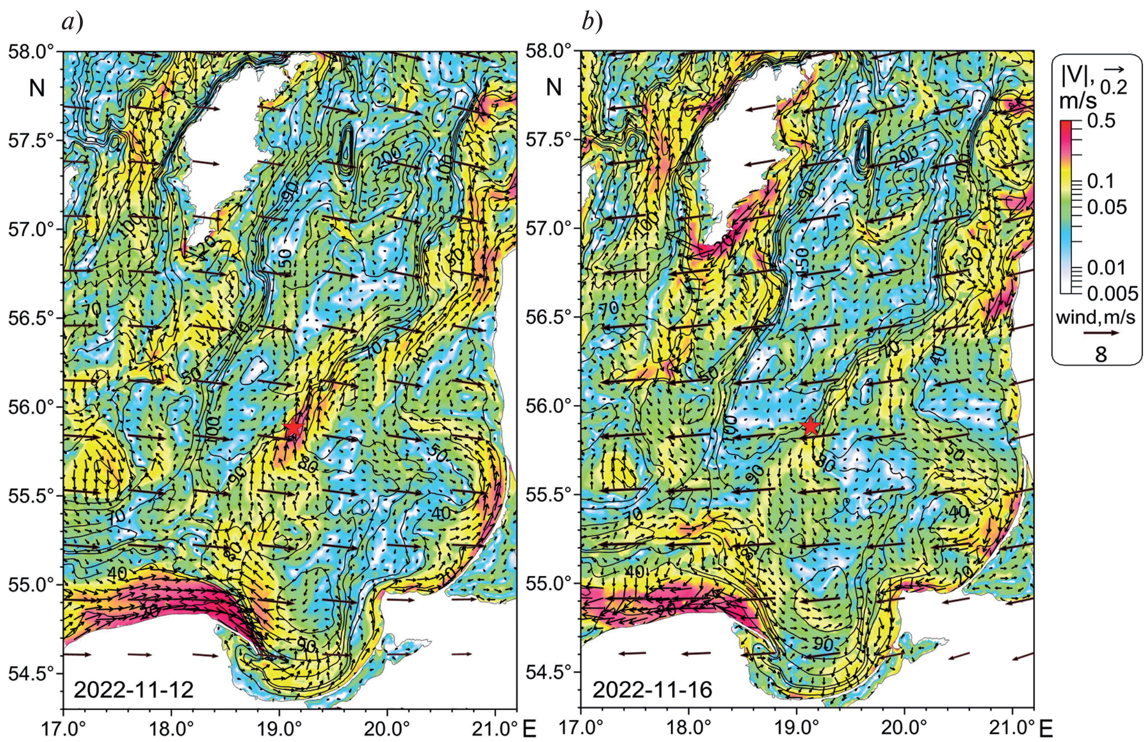

Fig. 6. Maps of the daily-averaged bottom layer currents (the small closely-spaced arrows and colors) simulated by NEMO for November 12 (*a*) and 16 (*b*), 2022 superimposed by the daily-averaged 10-m wind vectors (the large rarely-spaced arrows)

Following Zhurbas and Väli [15] and Zhurbas et al. [13], in order to find out which wind direction favours more/less the northward saltwater transport in HC, the correlation coefficient between the *v* component of the bottom layer velocity, both measured by TCM and simulated, and the projection of wind stress vector to the angle $\varphi \in (0°, 360°)$ was calculated from the 163 day time series (Fig. 7). The daily-averaged wind stress values were calculated as the arithmetic mean of 24 consecutive terms of the hourly wind stress time series, while the hourly wind stress values were estimated from the 10 m level wind using empirical bulk parameterization by Large and Pond [20]. It is seen from Fig. 7 that the maximum correlation between the *v* component of the bottom layer velocity and the wind stress vector projection was 0.55 (with the 95 % confidence limits of 0.44–0.65) at φ = 307° and 0.40 (with the 95 % confidence limits of 0.26–0.52) at φ = 326° for the TCM measurements and NEMO simulation, respectively.

To more clearly demonstrate the connection between the seven-day fluctuations in the northward saltwater flow in HC and wind conditions, Fig. 8 presents the low-pass filtered time series (periods ≥ 1 day) of the *v*-component of velocity measured by TCM and the projection of the 10 m wind vector to the angle φ = 296° (W_{10}(296°)) at which the correlation was maximum (0.54 with the 95 confidence limits of 0.42–0.64). During some periods of time the *v* and W_{10}(296°) time series display almost synchronous seven-day fluctuations. It can be considered convincing evidence that the seven-day fluctuations in the northward saltwater transport in HC were caused by wind forcing. The maximum correlation between *v* on the one hand and the projection of the wind stress vector or the projection of the wind velocity vector on the other hand is achieved at different, although quite close, angle values φ. In principle, one should not expect the exact coincidence of the angles φ, because the vectors of wind stress and wind velocity, coinciding in direction, are nonlinearly related in magnitude.

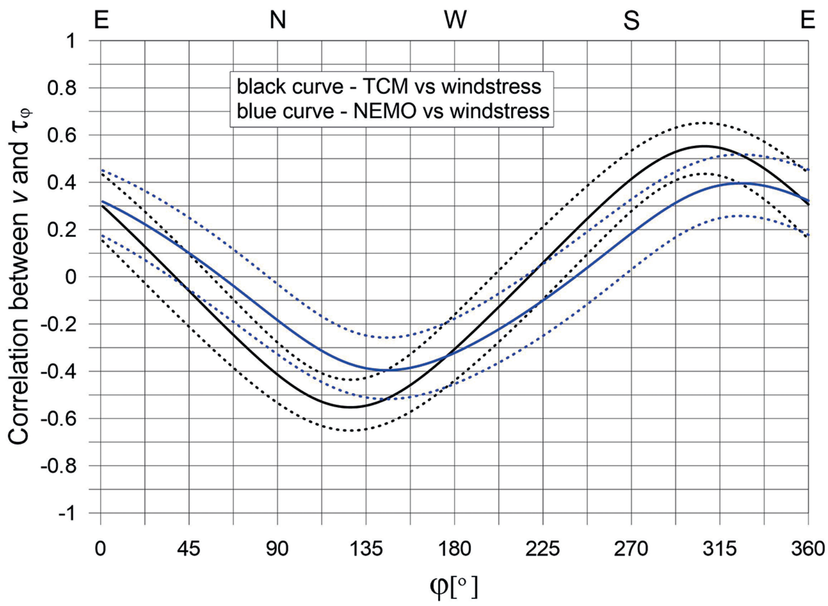

Fig. 7. Correlation between the north component of the bottom layer velocity *v* and the wind stress projection to the angle φ (solid curves). Dotted curves show 95 % confidence limits

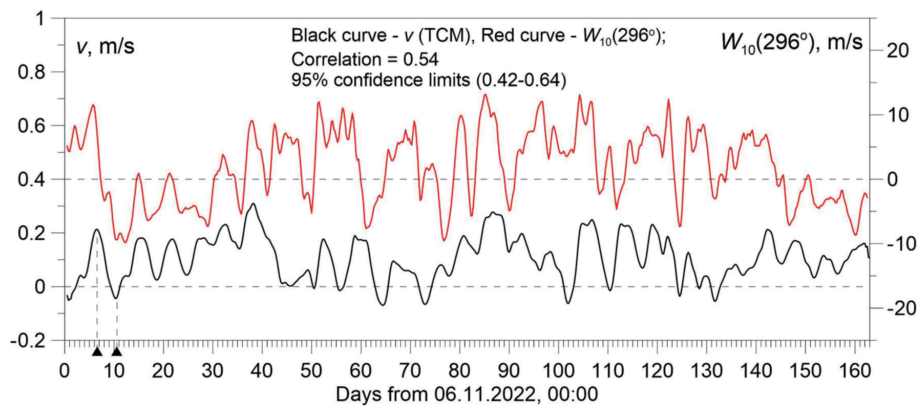

Fig. 8. Low-pass filtered time series (periods ≥ 1 day) of the *v* -component of velocity measured by TCM and the projection of the 10 m wind vector to the angle φ = 296° (black and red curves, respectively)

4. Discussion and conclusions

This paper presents in situ measurements in a very thin bottom layer (at 1 m height above the bottom) performed by TCM at the eastern slope of HC just on the pathway of saltwater flow to the Gotland Deep and its comparison with the results of modelling. The half-year-long time series of the bottom layer velocity measured in HC displayed seven-day oscillations of the northward saltwater flow. The flow was characterized by alterations of surges with the increase of northward velocity to approximately 0.2–0.3 m/s and blockages when the northward velocity vanishes or becomes small negative. The measured time series of the northward velocity component was surprisingly highly correlated with the simulation by NEMO reanalysis at the correlation coefficient of 0.82 and the 95 % confidence limits of 0.76–0.86. The only noticeable difference between the measurements and the simulation was found in the direction of the saltwater flow (see Fig. 4). The measured mean flow was directed at the angle $\varphi = 96°$ (i. e., to the north with a weak westward deviation), while the simulated mean flow at $\varphi = 74°$ (i. e. to the north with a considerable eastward deviation). The discrepancy in the direction of saltwater flow can be explained by the fact that in the Ekman bottom layer there is a deflection to the left (in Northern Hemisphere) of the flow above the layer (remember that the TCM measurements were carried out at $h = 1$ m above the bottom, while the simulated current corresponds to $h = 5.5$ m).

In principle the seven-day oscillations of the bottom layer velocity in HC could be assumed to be a distant response to the variability of saltwater inflow from the North Sea (though such possibility does not seem credible because the seven-day period is too small in comparison to typical timescales of the inflow variability). In this case, the v component of velocity oscillations would be positively correlated with salinity. On the contrary, if the seven-day oscillations are caused by wind forcing, the correlation between v and S is expected to be nil. In fact, correlation between simulated time series of the v and S fluctuations presented in Fig. 2 was –0.04 at the 95 % confidence limits of [–0.19, 0.11] which favors the wind forcing hypothesis. The absence of a statistically significant correlation between the v and S fluctuations indicates the minor role of seven-day velocity fluctuations in the overall salinity transport towards the Gotland Deep.

To find out which wind direction is most/least favorable for saltwater transport in HC towards the Gotland Deep, following [15] the correlation between the v component of the bottom layer velocity, both measured and simulated, and the projection of wind stress to the angle $0° \le \varphi < 360°$ was calculated. Similar to [15], the maximum correlation was for the angle range $307° \le \varphi < 326°$, i. e. for the northwest wind which is directed to the southeast perpendicularly to the right of the saltwater flow. In this case the wind-driven Ekman transport in the surface layer is directed to the southwest causing a compensatory saltwater countercurrent to the northeast in the deep layer of HC. However, in [15] the maximum correlation was 0.81 versus 0.40 and 0.55 in this study. Zhurbas and Väli [15] obtained considerably higher correlation between the saltwater flow and the southeast component of wind stress in HC because they characterized the saltwater flow by an integral, vertically averaged saltwater transport instead of the v component of velocity at a fixed level above the bottom used in this study.

The seven-day oscillations in the saltwater flow in HC were shown to be accompanied by almost synchronous oscillations of the southeast component of the wind vector (see Fig. 8). It can be considered convincing evidence that the seven-day oscillations were caused by wind forcing.

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